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OPTIMUM DESIGN FOR LRE CENTRIFUGAL PUMPS

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Zhu Zuchao Zhang Guoqian Sun Jiren

ABSTRACT

We set up a mathematical model to predict low specific speed LRE centrifugal pump unit performance. Using the model in question, performance predictions were carried out for 10 types of LRE centrifugal pumps. Relative errors between experimental values and predicted values associated with efficiency and lift were all within 4%. Using the model in question, design optimization with efficiency as the target function was carried out on AM-7H and O pumps as well as AM-1R pumps and AM-50 pumps. Results clearly show that, with a presupposition of surety systems possessing high vapor corrosion characteristics, the efficiencies of these four types of pumps can be respectively raised 6.5%, 5.22%, 5.2%, and 4.41%.

KEY WORDS: Liquid rocket engine, Centrifugal pump, Optimum design

I. LRE CENTRIFUGAL PUMP OPTIMUM DESIGN

LRE centrifugal pump units should possess good vapor corrosion characteristics, high efficiencies, good stability, and similar special traits. With a presupposition of satisfying vapor corrosion characteristics and operating stability, raising pump unit efficiency is the problem which this article wants to solve. Because of this, the article in question adopts efficiency to act as the target function associated with LRE centrifugal pump unit design optimization, taking vapor corrosion characteristics and stability to act as restraining conditions for purposes of treatments.

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* Numbers in margins indicate foreign pagination. Commas in numbers indicate decimals.

2. Mathematical Models

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LRE centrifugal pumps operate with rotational speeds which are much higher than centrifugal pumps for civilian use. Fluid flow speeds associated with vane wheels and the interiors of vortical casings are very great. In this way, hydraulic power losses increase. LRE centrifugal pump dimensions will also be smaller than pumps for civilian use. Their relatively high vapor corrosion characteristics require increasing intake diameters. High rotation speeds and active propellants require relatively large operating clearances. All these things cause the efficiencies of LRE centrifugal pumps--with the same sorts of specific rotational speeds n_s and flow amounts Q--to be lower than pumps for civilian use. Because of this, when setting up LRE centrifugal pump efficiency models, it is not possible to completely copy related models associated with pumps for civilian use indiscriminately.

1) Calculations of Various Loss Quantities

The various loss quantities that are considered by this article include vane wheel intake hydraulic flow shock ΔH_{sh} , vane wheel flow path friction loss ΔH_{fr2} as well as diffusion loss ΔH_{fr2}, vortical casing flow path friction loss ΔH_{sf} as well as diffusion loss ΔH_{sx} , diffuser loss ΔH_k , as well as vane wheel power depletion ΔP_d , and so on.

$$\Delta H_{sh} = k_1 \frac{W_1^2}{2g} \tag{1}$$

$$\Delta H_{fr1} = k_2 \lambda l / D_W \cdot W^2 / 2g \tag{2}$$

In the equations, l, D_W, E and lambda are, respectively, vane wheel flow path hydraulic length, diameter, relative speed and friction coefficient.

$$\Delta H_{fr2} = 0.2(W_2^2 - W_1^2)/g \tag{3}$$

$$\Delta H_{sx} = 0.2k_3 \frac{C_{u2}^2 - V_{TH}^2}{2g} \tag{4}$$

$$\Delta H_k = k_3 \zeta_s \frac{V_{TH}^2}{2g} \tag{5}$$

In the equations, ζ_s is diffuser diffusion coefficients

$$\zeta_s = \frac{\lambda}{\sin\frac{\gamma}{2}}(1 - n^{-2}) + \sin\gamma(1 - n^{-2})^2$$

n and γ are, respectively, diffuser area ratios and expansion angles.

$$\Delta H_{sf} = k_4 \lambda \frac{l}{d} \cdot \frac{V_{TH}^2}{2g} \tag{6}$$

In equations, l and V_{TH} as well as d are vortical casing lengths, vortical casing throat section speeds, and equivalent round tube diameters.

Overall hydraulic power losses $\Sigma\Delta H$ are:

$$\Sigma\Delta H = \Delta H_{sh} + \Delta H_{fr1} + \Delta H_{fr2} + \Delta H_{sx} + \Delta H_k + \Delta H_{sf} \tag{7}$$

$$\Delta P_d = 5.038 \times 10^{-3} k_5 C_a \rho U_2^3 \frac{D_2^2}{2g} \quad (\mathrm{kW}) \tag{8}$$

$$C_a = 0.0465 \sqrt[0.2]{\frac{U_2 D_2}{2\gamma}} \tag{9}$$

In the equations above, k_i (i=1,2,...5) are correction coefficients related to specific rotation speeds. /55

$$k_{i+1} = x_{3i+1} + x_{3i+2} \cdot n_s^{k_{3i+3}} \qquad i = 0, 1, \cdots, 4 \tag{10}$$

In this, x_i (i=1,2,...,15) are specific coefficients.

2) Prediction Models

LRE centrifugal pump efficiencies can be expressed as:

$$\eta = \frac{1}{\frac{1}{\eta_v \eta_h} + \frac{\Delta P_d}{N_e} + 0.05} \tag{11}$$

In the equation above, η_v and η_h as well as N_e are volume efficiencies, hydraulic power efficiencies, and effective powers.

$$\eta_v = \frac{1}{1.0 + 0.68 n_s^{-\frac{2}{3}}} \tag{12}$$

$$\eta_h = \frac{H}{H_{th} + H_{in}} \tag{13}$$

LRE centrifugal pump lift prediction models are as follows:

$$H = H_{ind} + (H_{th} - \Sigma \Delta H) \tag{14}$$

For calculations of induction wheel actual lift H_{ind} and theoretical lift H_{in} as well as centrifugal wheel theoretical lift H_{th}, see references [1] and [2].

3) Solution for the Constants x_i Awaiting Specification

When calculating ΔH_{sh}, ΔH_{fr1}, ΔH_{k}, ΔH_{sx}, ΔH_{sf} as well as ΔP_d above, we introduced the correction coefficients k_i (i=1,2...5). Among these are included 15 coefficients awaiting specification x_i (i=1,2...15). Below, we use direct P-H optimization methods in order to solve for xi. With a view toward LRE centrifugal pumps, statistical calculations were carried out on their properties. In conjunction with this, taking equation (15) to act as the target function, x_i was taken to act as the optimization variable, and optimization calculations were carried out, causing calculated efficiencies and actual efficiencies, calculated lifts and actual lifts, to have the most proximate levels.

Minimization $$F(X)=\left[\frac{1}{N}\sum_{i=1}^{N}(\eta_{ri}-\eta_i)^2\right]^{0.5}+\left[\frac{1}{N}\sum_{i=1}^{N}\left(1.0-\frac{H_i}{H_{Di}}\right)^2\right]^{0.5} \quad (15)$$

causes agreement with:

$$0.20 \leqslant k_{i+1}=x_{3i+1}+x_{3i+2}\cdot n_s^{x_{3i+3}} \leqslant 1.5 \quad i=0,1\cdots,4$$

Use is made of P-H [3] methods to solve for x_i as below:

$$x_{1\sim 5}=0.7884,\ -1.5958,\ -1.0124,\ 14.1687,\ -14.2856$$
$$x_{6\sim 10}=0.004796,\ 3.0631,\ -2.7985,\ 0.005481,\ 1.0341$$
$$x_{11\sim 15}=-0.6642,\ -4.1812,\ 0.7637,\ 0.006831,\ 0.5855$$

These 15 constants connect equation (1) ... equation (14) and together form mathematical models for LRE centrifugal pump unit characteristic predictions.

4) Characteristic Prediction Cases

Using the models in question, performance predictions were carried out on 10 types of LRE centrifugal pumps. From Table 1, one learns that there is good agreement between predicted values and actual values associated with design operating status points. Maximum relative efficiency error is 3.87%. Besides the relative lift error associated with AM-2R pumps being 4.90%, the rest are all within 4%. It is possible to see that prediction precision is very satisfactory.

3. Design variables

Design variables adopted by this article include induction wheel intake flow amount coefficients ψ_{ind}, intake diameter ratios R_d, and intake flow fluid angles of attack α_{ind},

TABLE 1. LRE CENTRIFUGAL PUMP UNIT PERFORMANCE PREDICTION VALUES AND EXPERIMENTAL VALUES

(1) 型号		AM-7		AM-2		AM-3		AM-4		AM-1	
(2) 泵别		H	O	Y	R	Y	R	Y	R	Y	R
η^*	%	56.5	68.0	72.1	67.4	73.1	68.6	65.9	59.9	63.2	65.7
η	%	55.0	70.3	75.0	68.0	74.0	67.0	64.0	61.0	62.0	64.3
$\sigma_{\eta R}$	%	2.72	3.3	3.87	0.88	1.21	2.39	2.97	1.80	1.94	2.18
H	m	6276	383	723	1568	954	1904	802	1260	617.4	1034
H_D	m	6289	398.8	721	1495	960	1885	824	1291	606.6	1030
H_s	m	6369	396	740	1517	989	1947			642	1062
σ_{HR}	%	0.21	3.96	0.28	4.90	0.63	1.0	2.67	2.25	1.75	0.39
σ_{HR1}	%	1.77	3.3	2.3	2.36	3.54	2.2			3.87	2.63

Key: (1) Model (2) Pump Specification

Note: $\sigma_{\eta R}=\frac{|\eta'-\eta|}{\eta}$ $\sigma_{RH}=\frac{|H'-H_c|}{H_c}$ $\sigma_{HR1}=\frac{|H'-H_s|}{H_s}$

Items carrying a' are prediction values from this article. H_c and H_s are design and experimental lifts.

α_{ind} installation angles β_1 and β_2 of intake and exhaust blades associated with centrifugal wheels, intake and exhaust diameters D_1 and D_2, intake and exhaust widths b_1 and b_2, blade numbers Z, as well as vortical casing throat areas F . That is:

$$X=(\Psi_{ind},R_d,\alpha_{ind},D_2,D_1,b_2,b_1,\beta_2,\beta_1,F,Z)^T$$

4. Restraining Conditions

1) Restraining Conditions Determined by Design Requirements

LRE centrifugal pump unit induction wheel vapor corrosion specific rotation speeds C_{kpi} should be larger than pump unit critical vapor corrosion specific rotation speeds C_{kpl} or larger than vapor corrosion specific rotation speeds C_{onst} associated with design requirements, that is:

$$C_{kpi} - 1.36 \cdot C_{kpl} \geqslant 0 \tag{16}$$

$$C_{kpi} - C_{onst} \geqslant 0 \tag{17}$$

Besides this, in order to guarantee the lack of vapor corrosion fractures in operating states, induction wheel lift H_{ind} should be accurately specified according to the equation below:

$$0.08 \leqslant \frac{H_{ind} + NPSH_i - NPSH_r}{\frac{U_D^2}{g}} \leqslant 0.15 \tag{18}$$

In equations, $NPSH_i$ and $NPSH_r$ as well as U_D are circular velocities associated with diameter location induction wheel gas corrosion margins, centrifugal wheel intake dynamic pressure drops, and induction wheel calculations.

(2) Lifts H produced by pump units should be larger than design lifts H_D, that is:

$$H_{ind} + (H_{th} - \Sigma \Delta H) - (1.01 \sim 1.03) \cdot H_D \geqslant 0 \tag{20}$$

(3) Centrifugal wheels must not give rise to the appearance of flow disengagement and loss of speed, that is:

$$0.8 \leqslant \frac{W_1}{W_2} \leqslant 1.4 \tag{21}$$

2) Selection Ranges for Design Variable Values and Additional Restraints /57

Their precise specification will be explained in concrete examples.

5. Optimum Design Cases and Analyses

Below we take the AM-1R pump as an example and carry out LRE centrifugal pump unit optimum design. The design parameters are as follows:

Flow Amount $Q=0.0394m^3/s$ Design Lift $H_D=1030m$

Revolution Speed $n=16500r/min$ Specific Revolution Speed $n_s=65.3$

On the basis of AM-1R pump original structural dimensions, we give design variable ranges and additional restraints as below:

$$0.065 \leqslant \Psi_{ind} \leqslant 0.135 \qquad 3.0^\circ \leqslant a_{ind} \leqslant 7.0^\circ$$

$$0.16 \leqslant R_d \leqslant 0.25 \qquad 0.6D_2' \leqslant D_2 \leqslant 1.4D_2'$$

$$0.3 \leqslant \frac{D_0^2 - D_{hi}^2}{4D_1 b_1} \leqslant 1.0 \qquad 0.65 \leqslant \frac{D_1}{D_i} \leqslant 0.95$$

$$16^\circ \leqslant \beta_1 \leqslant 25^\circ \qquad 18^\circ \leqslant \beta_2 \leqslant 60^\circ$$

$$0.6b_2' \leqslant b_2 \leqslant 1.4b_2' \qquad 0.7F' \leqslant F \leqslant 1.3F'$$

$$\beta_2 - \beta_1 \geqslant 0 \qquad 6^\circ \leqslant \beta_{1\,ind} \leqslant 15^\circ$$

$$8^\circ \leqslant a_{imp} \leqslant 16^\circ \qquad \Delta\beta_i \geqslant 0$$

On the basis of actual states of LRE centrifugal pumps, we get empirical formulae for the calculation of D_2, b_2, and a_{ind} as follows:

$$D'_2 = 19.2\left(\frac{n_s}{100}\right)^{1/6} \cdot \frac{\sqrt{2gH_D}}{n} \qquad b'_2 = 2.413\left(\frac{n_s}{100}\right)^{0.9768} \cdot \frac{\sqrt{2gH_D}}{n}$$

$$F' = \frac{Q}{(0.661 - 0.00235 n_s)\sqrt{2gH_D}}$$

In situations with a centrifugal wheel blade number Z=7, the results and original parameters are shown in Table 2. From Table 2, one learns that, with a presupposition of surety system vapor corrosion performance, efficiencies are raised from the original 64.3% to 69.5%, that is, an increase of 5.2%.

TABLE 2. COMPARATIVE PARAMETER TABLE FOR AM-1R PUMPS BEFORE AND AFTER OPTIMIZATION

(1) 名 称	D_1(mm)	ψ_{ind}	R_d	α_{ind}	β_{1ind}	b_1	b_2	D_1	D_2
(2) 实际值	84	0.1081	0.238	4.98	11.15	32	15	70	153.8
(3) 优化值	79.24	0.1282	0.226	6.4	14.36	26	14.7	74.4	153
(1) 名 称	β_1	β_2	α_{imp}	F	ΔH	C_{kp}	W_1/W_2	H(m)	η
(2) 实际值	20	24.07	7.51	6.24	229	4404	1.31	1030	64.3%
(3) 优化值	16.8	37.51	7.75	6.84	168.7	4172	1.218	1048.5	69.5%

Key: (1) Nomenclature (2) Actual Value (3) Optimization Value

Besides this, optimum designs were also carried out for AM-70 and H pumps as well as AM-50 pumps. The design parameters are shown below. From the table below, one knows that efficiencies associated with these three types of pumps after optimization are capable of, respectively, increasing 5.22%, 5.9%, and 4.41%.

(1) 离心泵名称	Q (m^3/s)	H_D	n(r/min)	n_s	(2) 实际效率	(3) 优化后效率
AM-70泵 (4)	0.00806	398.85	18480	68	70.3%	75.52%
AM-7H泵 (4)	0.02592	5949	36960	32.06	55.6%	61.54%
AM-50泵 (4)	0.01383	558.3	20000	74.74	66%	70.44%

Key: (1) Centrifugal Pump Nomenclature (2) Actual Efficiency (3) Efficiency After Optimization (4) Pump

II. CONCLUSIONS

1. This article set up mathematical models for predicting LRE centrifugal pump performance. Using the models in question, predictions were carried out for 10 types of LRE centrifugal pumps. The results clearly showed that the relative errors between predicted values and actual values associated with efficiencies and lifts were all within 4%.

2. This article set up optimum design methods for LRE centrifugal pump units. Optimization was carried out on AM-1R pumps, AM-70 pumps, II pumps, and AM-50 pumps. The results clearly showed that, with a presupposition guaranteeing that pump units possess high vapor corrosion performance, the efficiencies can respectively go up 5.2%, 5.22%, 6.5%, and 4.41%.

3. This article gives performance prediction and optimum design programs with strong general utility, fast computation speeds, and high precision. They are capable of use in the test manufacture of current and future LRE centrifugal pumps and CAD advances. In the design of centrifugal pumps for civilian use, they also have very great significance.

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